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2000 V 6H-SiC pn junction diodes

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ABSTRACT: This paper reports on the fabrication and electrical characterization of the first silicon carbide diodes to demonstrate rectification to reverse voltages in excess of 2000 V at room temperature. The 6H-SiC p^+n mesa diodes were fabricated in 6H-SiC epilayers grown at NASA Lewis by atmospheric pressure chemical vapor deposition on commercially available 6H-SiC wafers, which produced the $N_D < 5 \times 10^{15}$ cm^{-3}, 24 μm thick n-type layer needed to standoff two kilovolt reverse potentials. The devices were initially characterized immersed in Fluorinert™ to prevent the sparking that occurs when air breaks down under high electric fields. The simple non-optimized mesa process, which employed no explicit junction field termination geometries, exhibited a 2000 V functional device yield well in excess of 50%, although device areas were limited to 4×10^{-4} cm^2 or less.

1. INTRODUCTION

A recent appraisal conducted by Bhatnagar and Baliga (1993) indicates that SiC power MOSFET's and diode rectifiers would operate over higher voltage and temperature ranges, have superior switching characteristics, and yet have die sizes nearly 20 times smaller than correspondingly rated silicon-based power devices. Unfortunately, at least several crucial fabrication issues must be solved before these fantastic theoretical advantages SiC power devices can be realized experimentally. One such issue is that for SiC power devices to standoff multi-kilovolt potentials, epilayer doping concentrations must be reduced. Using a novel dopant control process developed by Larkin et al (1993), doping concentrations in 6H-SiC epilayers grown by atmospheric pressure chemical vapor deposition have been substantially diminished. This advancement has enabled the fabrication of the first 2000 V silicon carbide diode rectifiers (Neudeck et al 1993).

2. DEVICE FABRICATION

The 6H-SiC epilayer structure shown in Figure 1 was grown on a substrate cut from a Cree silicon-face 6H-SiC wafer polished 3° to 4° off the (0001) basal plane. The system and general growth procedures are described elsewhere (Powell et al 1992a and b), but the key lightly doped blocking voltage layer was grown with the improved dopant control process reported by

Larkin et al (1993) at this conference. Following growth a 2000 Å thick aluminum etch mask defining circular and square diode mesas, ranging in area from 7 x 10^{-6} cm^2 to 4 x 10^{-4} cm^2, was applied and patterned by liftoff. The diode mesas were etched to a depth of approximately 6 μm using reactive ion etching in 80% SF_6 : 20% O_2 under 300 W rf at a chamber pressure of 250 mTorr. Unpatterned electron beam evaporation of aluminum onto the backside of the wafer completed the fabrication process. No contact anneals were performed in this work for the simple reason that the measurement of fundamental rectification properties could be accomplished without minimizing contact resistances.

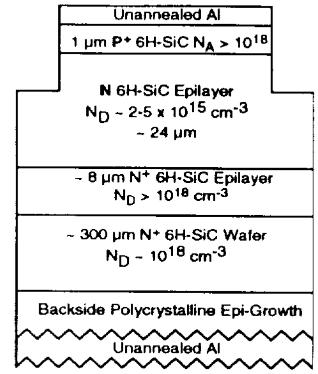

Fig. 1. Diode cross-section.

3. ELECTRICAL MEASUREMENTS

All electrical measurements were carried out in the dark on a probing station using computer controlled current-voltage (I-V) and capacitance-voltage (C-V) instrumentation. I-V characteristics above and below -1100 V were measured with different instruments due to measurement equipment resolution and operating voltage limitations. The apparent carrier concentration of the lightly-doped n-type blocking voltage layer, as measured at room temperature on the largest-area diodes by 100 KHz and 1 MHz C-V techniques, was within the range of 2 - 5 x 10^{15} cm^{-3}. When probed in air, the diodes exhibited excellent rectifying characteristics as long as reverse-bias voltages were held below 300 V to 400 V. The application of larger reverse voltages resulted in destructive electric arcs emanating from the device mesa periphery. Based on the previous experience of Matus et al (1991) that the air around the device was associated with high-voltage diode failure, the sample was immersed in a shallow tub filled with Fluorinert™ FC-77 (a high dielectric strength insulating fluid) for all of the high-voltage testing beyond 300 V reverse bias.

When immersed in clean Fluorinert™, the devices exhibited room-temperature rectification to reverse voltages in excess of 2000 V as shown in Figure 2. Over half of the diodes tested in fresh Fluorinert demonstrated 2000 V blocking voltages, and the maximum rectifying voltage observed was 2200 V. This represents the highest blocking voltage ever reported in a silicon carbide diode, surpassing the largest previously reported silicon carbide diode rectifying voltage reported by Edmond et al (1991) by over 600 V. The reverse I-V of Figure 3 is typical, but leakage current variations by as much as an order of magnitude above and below the Figure 3 characteristic were measured.

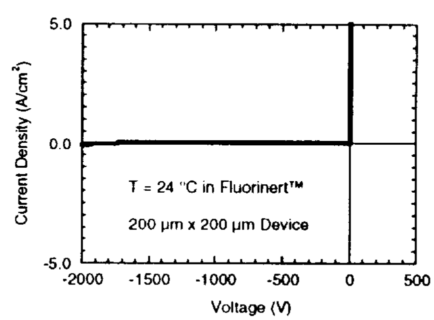

Fig. 2. Linear I-V characteristic at 300K

In clean Fluorinert™, the diodes failed catastrophically between 2000 V and 2200 V reverse bias, but the exact mechanism for this

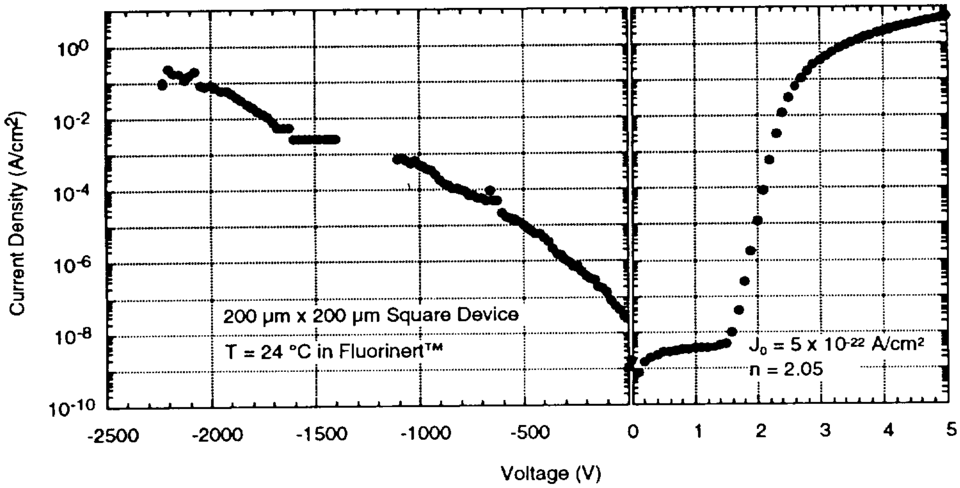

Fig. 3. Semi-logarithmic 6H-SiC pn diode I-V characteristics at 300 K.

failure is unclear at this time. No evidence of avalanche breakdown was observed in any I-V measurements. Despite attempts to limit excessive current flow during testing, the high-voltage reverse failure events were so catastrophic that the device mesas were destroyed as shown in Figure 4. The arcing residues at the crater sites left behind by device annihilations appear to suggest that failure is occurring along the mesa periphery, possibly due to dielectric failure of the Fluorinert™ under excessively high electric fields. A supporting observation as to the role of the Fluorinert™ in device failure was that the highest blocking voltages were only obtainable in solutions of fresh, clean Fluorinert™. The measured catastrophic failure voltages of diodes on the wafer declined when a given tub of Fluorinert™ degraded after the destructive testing of a few diodes, presumably a result of chemical breakdown or the presence of particulate debris generated by the catastrophic failures. Maximum high-voltage performance on non-damaged devices was restored only when the tub and wafer were solvent cleaned and dried and the sample re-immersed in fresh Fluorinert™.

The forward characteristics of the diodes were very well behaved, exhibiting saturation current densities below 10^{-20} A/cm^2 and consistent ideality (n) factors very close to 2. The series resistance demonstrated by the non-exponential behavior above 2.5 V forward bias is around 0.3 Ω-cm^2. This specific on resistance is roughly an order of magnitude larger than the specific on resistance theoretically calculated for the lightly doped 24 µm thick drift region, but

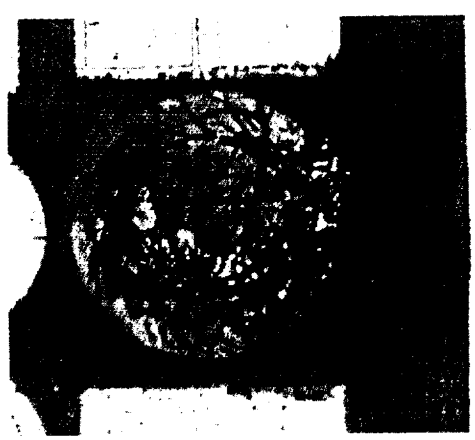

Fig. 4. Diode following catastrophic failure.

this is likely due to parasitic series resistance arising from non-optimized unannealed ohmic contacts and the presence of backside polycrystalline SiC material deposited onto the bottom of the wafer during the epitaxial growth.

4. DISCUSSION AND SUMMARY

Even though avalanche breakdown was not observed in the diodes, it is nevertheless useful to estimate the peak electric field in the devices. First-order single-sided p^+n junction calculations indicate that the junction depletion might extend through the entire 24 µm thick n layer at 2200 V reverse bias, so the possibility of depletion layer reach-through to the buried n^+ epilayer was accounted for in the calculations (Neudeck 1991). Peak junction electric field values of 1.4 - 1.8 MV/cm were calculated for the 2 - 5 x 10^{15} cm^{-3} measured doping range. These values fall just below the low-doped junction breakdown fields predicted by extrapolation of measured breakdown data of Edmond et al (1991) from more highly-doped ($\sim 10^{16}$-10^{19} cm^{-3}) junctions.

In summary, we have produced the first silicon carbide diodes to achieve rectification to reverse voltages in excess of 2000 V, representing a 600 V improvement in reported silicon carbide diode blocking voltage capability. A functional yield of over 50 % was obtained on these small-area prototype diodes, but it is important to note that micropipes and possibly other defects documented Koga et al (1992), Neudeck et al (1993), and Powell et al (1993) in 6H-SiC wafers and epilayers will likely cause difficulties as device areas are enlarged. The reduction of such defects and the continued improvement of SiC epitaxial growth, ohmic contact, and dielectric passivation technologies will be crucial areas of continued research towards the realization of highly advantageous silicon carbide power devices.

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